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PRECISION AND LOW COST POSITION DETECTION USING CAPACITIVE SENSOR TECHNOLOGY

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ABSTRACT

In the wide application range of measurement, position detection is common indispensable. Beside pure position detection it is also used for force transducers and precision balances.

Using the example of a scale, which depends on the electromagnetic force compensation principle (EMC-scale, cf. [1]), the application of an alternative capacitive measuring method will be specified in the following.

1. INTRODUCTION

To get an overview of an EMC-scale the principle of such a weight measurement system is shown in figure 1.

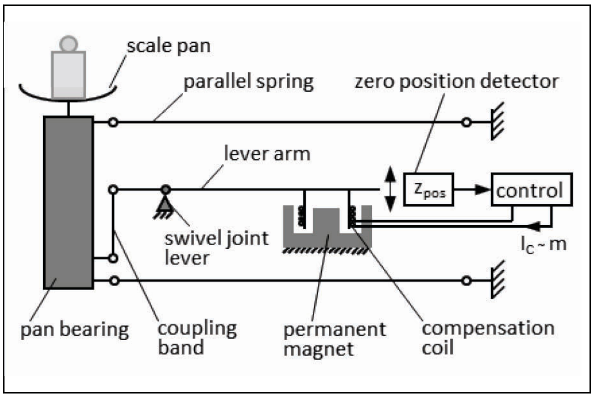

Fig. 1: EMC-scale principle

By putting a weight on the scale pan the lever arm is deflected from its zero position. This deflection is recognized from a zero position detector. Last-mentioned is part of a control, which controls the current through a compensation coil so that the lever arm will get back to its zero position due to Lorentz force.

Thus the weight could be set to a proportional current value.

Presently, the required position detection of an EMC-scale lever arm is handled with an optical position detector. It consists of a light source, a differential photodiode and a slit aperture, which is mechanically connected to the lever arm. The aforementioned measurement system indeed offers a well-balanced behavior between resolution and measuring range, however drift phenomena of the differential photodiode and comparatively high costs are negative factors for the measuring system. Furthermore, so far only an analog measurement signal is used for additional control.

An alternative to this is the link between the already known capacitive sensor technology and the relatively new microelectronics.

This provides, to the same degree as the optical measuring method, a high resolution over a wide range, but could be classified as more cost effective due to its simpler design and lower circuit complexity. It is also suitable for vacuum applications.

2. CAPACITIVE SENSOR

The underlying measurement principle of a capacitive measurement method is always based on a capacitance change. From the perspective of construction, the use of a differential capacitor assembly with two fixed and a movable electrode in accordance with figure 2 is recommended [2, 3].

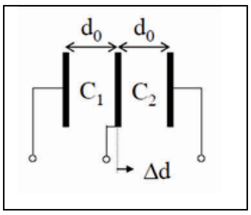

Fig. 2: Ideal differential capacitor with spacing variation [4]

For the differential capacitance ΔC between the capacitances C_1 and C_2, in the ideal homogeneous case and out depending on a change in distance of the movable plate from its neutral center position is applicable, as is known:

$$\Delta C = -2\,\varepsilon_0\,\varepsilon_r\,A\;\frac{\Delta d}{d_0^2 - (\Delta d)^2} \qquad (1)$$

Advantages of this arrangement are:

- Doubling the sensitivity in comparison to a two plate capacitor
- The differential capacitance ΔC is zero in the neutral center position
- A possible tilting of the movable electrode plate around its own axis in a parallel arrangement of the fixed electrodes does not take an effect
- In the center position the electrostatic force is theoretical zero
- The differential assembly results in a lower temperature and humidity dependence, because of their congenerous influence in both capacitances

A disadvantage of this arrangement is the possible contacting between the two electrode plates due to excessive deflection. Suitable alternative arrangements are part of the current ongoing research.

3. ELECTRONICS

According to the constructive dimensioning the downstream electronics is of significant importance.

3.1. Overview

There are a number of different possibilities, which can be reduced mainly to the following circuit principles:

- Voltage divider circuits
- AC bridges
- Resonance methods
- RC- and LC-oscillators
- Charge and discharge methods

Voltage divider circuits are simple designed amplitude-analog circuits, in which the capacitance is used as measured impedance. They show a great dependence on parasitic impedances. This can be compensated by the use of higher source frequencies, although this leads to greater problems in amplitude measurement and lower resolution. [7]

Alternating current bridges are the most common used amplitude-analog method [8]. With a differential capacitor a linear behavior between bridge voltage and distance-dependent deflection could be described. However, the AC bridge also shows the same problems as the voltage divider circuits.

The resonance method is based on voltage divider circuits with a voltage source in resonance mode (cf. [17]). It is used for measurement of the capacitance and its loss resistance. A compensation of stray capacitances is possible, cf. [6]. Because of the necessary adjustment and detection of the resonance condition this method is not suitable for fast measurements [6].

There are lots of different oscillator circuits known from literature (cf. [8, 9, 10]). Generally the to be measured capacitance is the frequency-determining element in such an oscillator circuit.

RC oscillators can be characterized by its easy design and independence from analog voltage levels [7]. Because of their non-usage of inductivities it is possible to adapt them into integrated circuits [4]. Disadvantages are poor frequency stability [8], low sensitivity in the field of small capacitance changes and bad stray capacitance immunity [6].

With the help of LC oscillators the dynamic range could be extended up to several hundred MHz [11]. A problem is the construction of a temperature- and timestable inductivity, which leads to higher component costs [4]. The hysteresis dissipation of the ferrite coil core is another disadvantage. A solution for this could be the use of an air coil, but this substantially reduces the value of inductivity and the descriptiveness over 10 MHz is difficult [12]. A drawback is also that stray capacitances are going into the measurement result.

The charge and discharge principle is based on charge and discharge of a measurement capacitance (cf. [13, 14]). Mostly this is made in comparison to another reference capacitance. Advantages of this method are low temperature drifts, a possible dependence only on the DC component of the discharge current pulses and an almost independence from ohmic losses in the capacitor [6]. A negative fact is the non-immunity towards stray capacitances [6].

3.2. Integrated circuits

For some time more and more integrated circuits are used for measurement purposes. They made it possible to develop a compact and low-priced measurement system with a low fault liability.

The market offers a wide range of different capacitive analog-digital transducer, based on one or more of the aforementioned circuit principles.

Most circuits are designed for touch sensors with high base capacitances, wide ranges, low resolution and lots of measuring channels.

Currently, only a few circuits are available for high precision capacitive measurement. With comparison of their characteristics (cf. [15]) an IC with integrated A/D-converter from Analog Devices could be found. The converter AD7747 is especially designed for measurement of a differential capacitor in a range of ±8 pF [5]. It based on the charge- and discharge method, which is recommended for precision measurements at high frequencies [6]. The possible maximum effective resolution is 19 bits (circa 20 aF) [5], however this could be achieved only at low update rates. The measurement frequency is limited to 45.5 Hz [5].

For further considerations the capacitive A/D-converter AD7747 and a differential capacitor, as shown in figure 2, will be used.

4. MEASUREMENT ARRANGEMENT

Aim was it to use a differential capacitor for zero position detection of an EMC-scale lever arm. At this, the position of a movable electrode depends on the measurement weight and the current through compensation coil.

For first experiments a simpler construction as the EMC-scale has been chosen. Therefore, a parallel spring arrangement, according to figure 3, was used.

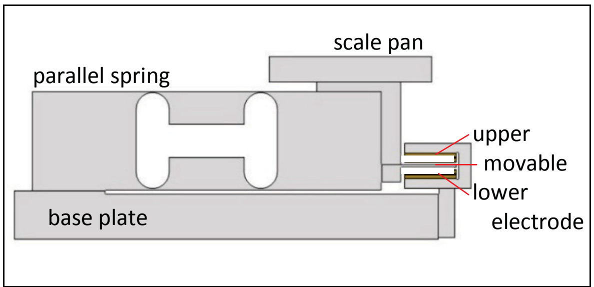

Fig. 3: Differential capacitor arrangement

The electrode area is about 2.25 cm² each, with a plate spacing of circa 500 µm in zero position. The upper and lower electrodes are isolated to the rest of this arrangement, while the moveable plate is electrically connected to the parallel spring.

With the help of this aperture the to be measured differential capacitance could be related to a variable weight reference level.

For computer-aided measurement data evolution the electrodes are electrical connected to the A/D-converter via coaxial cable. With the help of the “IO-Warrior24” from “Mercenaries Hard- und Software GmbH” (datasheet see [16]) the I²C signal is transformed to USB. In figure 4 the signal flow is shown.

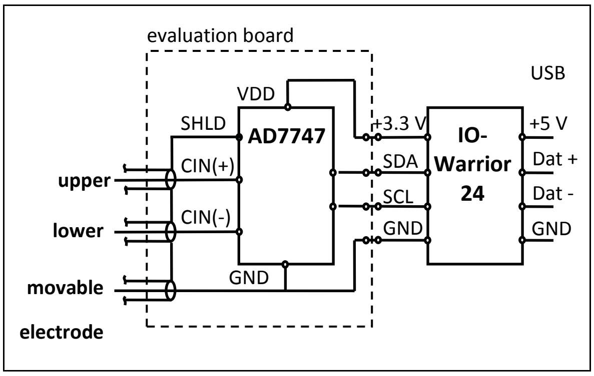

Fig. 4: Signal flow from differential capacitor to PC

The AD7747 supports a special shield pin, which could be utilized for a guard ring electrode configuration. In this experimental arrangement it was only used for cable shielding.

A software for different measurement tasks was realized in Visual Basic.

In mechanically unloaded state the movable electrode is near the upper ones and has the maximum positive deflection. By loading the support arrangement with different precision weights on the scale pan a deflection of the movable capacitor plate from the top towards the bottom electrode is followed. The differential capacitance can thus be taken as a function of weight.

In addition the deflection was determined with help of an interferometer, aligned on a reflector at the scale pan.

5. MEASUREMENT

5.1. Linearity

By application of various weights the linearity characteristic of the differential capacitance and the interferometric distance measurement can henceforth be determined proportional to the weight. The characteristic was measured in the range from 0 to 130 gram in each steps of 1 gram. Per step 100 single values were recorded at the maximum possible update rate of 45.5 Hz. Because of the only relative interferometric measurement the vibrometer was set to zero before starting with weight load (0 g) and was periodical set to zero with unloaded scale pan. In figure 5 the linearity behavior is shown.

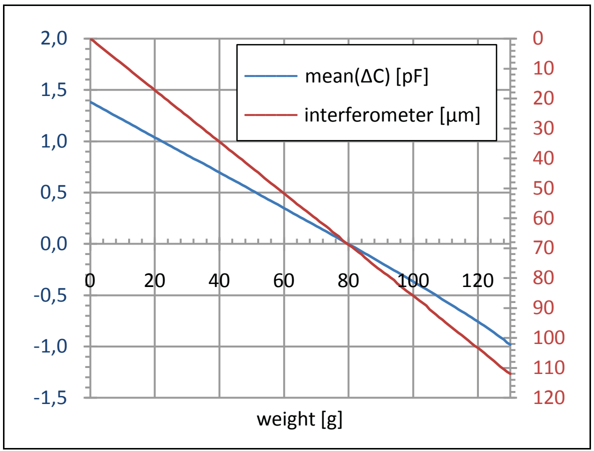

Fig. 5: Linearity measurement
(100 single measurements per gram)

From the above illustration it appears that the mean value of differential capacitance ΔC over a wide deflection range shows almost a linear behavior. Deviations are found especially in the area of small electrode gaps, where greater stray capacitances influence the measurement result. Furthermore an asymmetry can be recognized, this is resulting from a non right zero calibration.

By linearization of the measured capacitive curve the following straight line equation could be described (with x in g and y in pF):

$$y = -1.785130 \cdot 10^{-2} \frac{pF}{g} x + 1.405763\,pF \quad (2)$$

With this formula a sensitivity of circa 17.9 fF/g is resulting.

Figure 6 shows the area around the zero position of the differential capacitor in more detail.

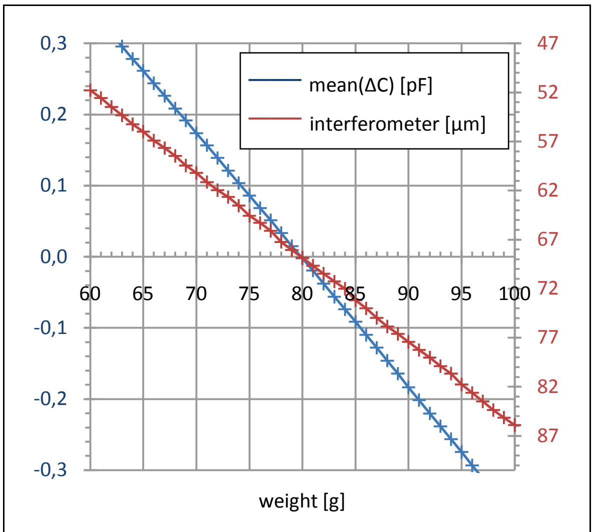

Fig. 6: Linearity measurement in detail
(100 single measurements per gram)

This is of great importance, because in this area the differential capacitor should work as a zero position detector, so a high resolution is needed for position detection performance.

Both, vibrometer and differential capacitance, illustrate a good linearity in this detailed view, which could be basically used for further control purposes.

By illustration of the differential capacitance to the interferometric distance (see figure 7) and linear regression the relation between the mean of the differential capacitance y (in pF) and interferometric displacement x (in nm) could be described as:

$$y = -2.072418 \cdot 10^{-5} \frac{pF}{nm} x + 1.405141\,pF \quad (3)$$

Thus a sensitivity about 20.7 aF/nm could be calculated for the measured curve.

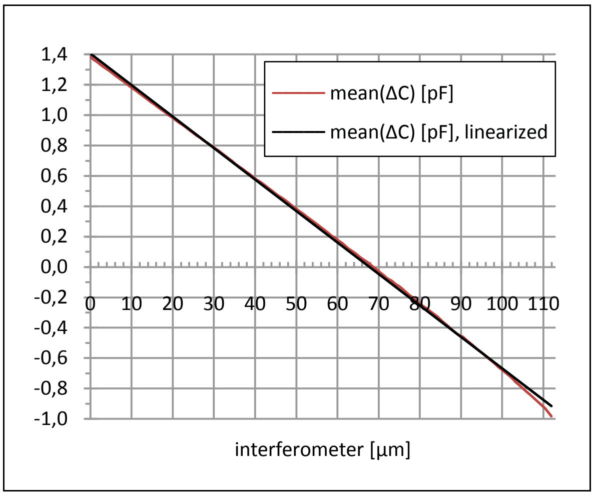

Fig. 7: Differential capacitance to interferometric distance

From the deviation of 100 single measurements per step a mean value of deviation of circa 33 nm could be calculated. It can be concluded, that it is not sufficient to take one or only a few single capacitive values to suggest a deflection. This can only be solved by averaging, which leads to a decrease of dynamics.

5.2. Long term stability and temperature influence

To get more information about the long term stability a measurement over 55 hours was recorded. Therefore the scale pan was unloaded and the differential capacitor was mechanical fixated. Both, mechanism and electronics were arranged in a thermally closed test cabinet. Figure 8 shows the measured curves of the differential capacitance.

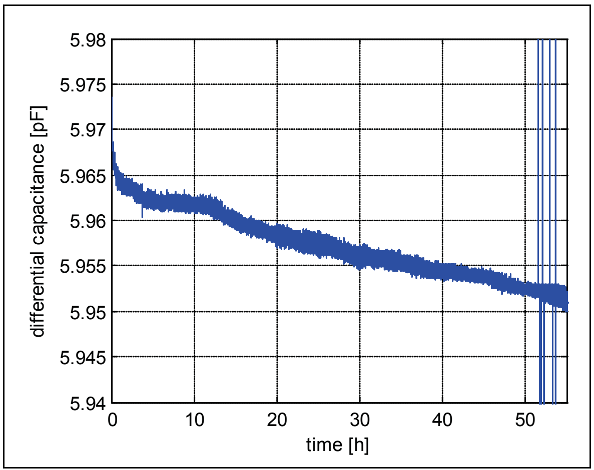

Fig. 8: Long term measurement with differential capacitance of AD7747, update rate: 1 Hz

Over the measurement duration of 55 hours a decreasing trend is resulting. From figure 8 it can be concluded, that this value is significant contingent to the initial and end region. In the initial area an exponentially decreasing trend is possibly a mechanical transient effect. The end area shows fast transients fluctuations, which perhaps are in fact of interference fields. By ignoring the last-mentioned two influences a peak to peak capacitive difference of 23.5 fF can be calculated. This leads to an approximately average drift of 0.4 fF/h. By use of formula 3 this means an average length drift of about 20.6 nm/h.

This effect may be a result of humidity and temperature changes as well as mechanical drifts.

Although humidity should not take an effect on measurement, if both capacitors of the differential capacitor arrangement are simultaneously changed, but if one capacitor is more influenced by humidity condensation this will lead to great errors in measurement of the differential capacitance.

Temperature during measurement was not stable at all (changes in the range from 23.3 °C to 27.1 °C). This means, that different coefficients of linear expansion could have an influence on the measurement, e.g. different electrodes enlargements. Furthermore the electric characteristic of the AD7747 depends on temperature with a capacitive gain drift of -28 ppm/K [5].

5.3. Noise behavior

With fixation of the experimental setup the noise behavior of the electronics can be, mostly independent from extern disturbances, explored in more detail. The noise behavior, as the calculated length deviation (by use of formula 3) from the mean capacitive value, is illustrated in figure 9. At this the movable electrode was located close to the zero center position.

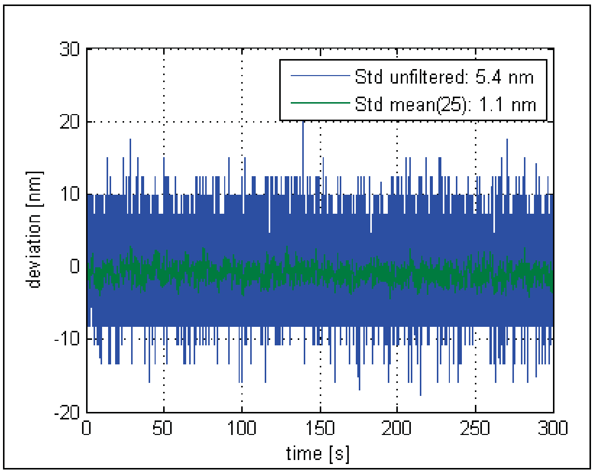

Fig. 9: Noise performance with max. update rate (45 Hz), blue unfiltered, green filtered

For the measurement values over a period of 5 minutes, a low standard deviation of 5.4 nm is resulting. This experimental value coincides well with the data sheet (cf. [5]) given capacitive values.

By the use of an average filter over 25 single measurement values a standard deviation of only 1.1 nm could be verified.

The resolution is therefore significantly limited by the noise performance of the electronics, but could be improved with the help of a simple filter.

6. CONCLUSIONS

Due to the high degree of linearity over a wide measuring range, the low noise performance and the cost-effective overall system the capacitive measurement method is an interesting alternative to former methods of position detection within an EMC-scale. Because of its small system size the ongoing trend of a growing miniaturization is also taken into account.

Approaches for further considerations are a modified construction of the differential capacitor, which should eliminate the influence of humidity and temperature, as well as an electronic circuit with higher dynamics for further control of the balance.

In addition the design of a mostly stray-immune overall system should be pursued.

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